REG NO. 1245-9
LOG NO. 9-9186

WT-1326

OPERATION REDWING—PROJECT 4.1

CHORIORETINAL BURNS

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ABSTRACT

Project 4.1 of Operation Redwing was a sequal to the study of chorioretinal burns during Operation Upshot-Knothole in 1953, in which nuclear devices in the range of 20 kt produced burns in the eyes of rabbits at distances of 2 to 42.5 statute miles from ground zero. Additionally four cases of accidental burns were produced at distances of 2 to 10 miles.

The Redwing study, reported herein, was designed to furnish supplemental information on the requirements for protection against retinal burns utilizing both rabbits and monkeys as experimental animals. Chorioretinal burns were produced by various segments of the thermal pulse. This was accomplished by two series of time-fractionating shutters. The first group, the early-closing shutters, were open at time zero and closed at increasing intervals of time. The second series, the delayed-opening shutters, were closed at time zero and subsequently opened for preselected time increments during the flash. The feasibility of protection by fixed-density optical filters was explored. Two types of developmental protective electronic shutters were field tested.

Results at yields of 15.9 kt and 340 kt demonstrated that the blink reflex does not protect against chorioretinal burns. Average blink reflex time (BRT) for rabbits was essentially the same on both shots: 362 and 382 msec at 340 and 15.9 kt, respectively. In contrast, the average BRT for monkeys at 160 msec for 14.9 kt nearly doubled to 293 msec for 340 kt. The 15.9-kt shot caused retinal lesions at 8.1 statute miles. The device of intermediate yield, 340 kt, produced burns at 7.5 miles but not as far as 14.4 miles. Additional information is needed in order to determine the limiting parameters for retinal burning over the entire range of weapon yield.

In the case of the 15.9-kt device, no burns were produced by the first pulse alone, which terminated at 13.1 msec. Retinal burns were not sustained until the interval of 0 to 67.5 msec was reached, after which the incidence was about 65 percent. The failure to produce injury by exposures of less than the initial 67.5 msec of the detonation discounts the contribution of the first pulse to burn production under the experimental conditions.

Four of thirteen exposures during the first pulse of the 340-kt device produced retinal burns, not including one case of shutter failure. Both explosions produced a number of burns during the second pulse. Of the rabbits protected only by their natural blink reflex, about 80 percent received burns at 8.1 miles from the 15.9-kt device and at 7.5 miles from the 340-kt device. In the comparable group of monkeys, 75 and 100 percent received chorioretinal burns from the smaller and larger devices, respectively. In both rabbits and monkeys, the 340-kt device at 7.5 miles produced lesions approaching one human optical disk diameter — about four times greater in diameter than those caused by exposure to the smaller device at about the same distance (8.1 miles). Evidence obtained on early closing shutters indicated that a dosage of about 20 to 30 mg cal/cm^2 at the cornea will produce burns during the initial 70 to 100 msec of the nuclear explosion.

Burns were not obtained from weapons of multimegaton yield at distances of 12.9 and 21.6 miles. Actually, the total thermal yield received at these distances was on the order of 1,800 mg cal/cm^2 and 1,000 mg cal/cm^2, respectively, which was ample for retinal burning. Although not conclusive, it appears that the low irradiance during the first 300 msec of the blast failed to deliver energy sufficient for burning before blinking oc-

curred, but possibly was enough to cause blinking that could provide protection during the remainder of the blast. Animals exposed at 10.7 miles from the 4.7-kt detonation did not receive burns. A contributing factor undoubtedly was attenuation by severe rain squalls at the time of detonation.

The optical filters tested at near-threshold distances prevented retinal burns. At intermediate distances, filters reduced the incidence and severity of the lesions. The results obtained on protective shutters were inconclusive with respect to protection against retinal burns; however, information was obtained invaluable to the future development of this equipment.

Loss of animals from sun stroke or heat prostration during the afternoon of D−1 threatened to be a problem, particularly where repeated shot postponement occurred after the animals were placed in the exposure racks. There was also some indication that light reflected to the unexposed eye may have caused blinking before certain of the shutters opened. Recommendations include provision for a trailer type of exposure facility, light-tight and airconditioned.

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Chapter 3

RESULTS and DISCUSSION

Chorioretinal burns were sustained on two shots, Erie and Mohawk. Detailed results on these shots are found in Tables 3.2 through 3.10. No burns were sustained on four shots, Lacrosse, Cherokee, Zuni, and Navajo, apparently because of a low radiant dosage during the period of the blink reflex. Parameters of blink-reflex exposures for all six shots are summarized in Table 3.1. Blink-reflex exposures are those that were limited only by the blink-reflex response of the individual animal, in contrast to other exposure series (which were accomplished behind early-closing, delayed opening, and protective shutters).

Chorioretinal burns were subjectively classified according to ophthalmoscopic appearance as mild, moderate, or severe. Lesion size was related to the human optic disk diameter (Figure 3.1).

3.1 SHOT ERIE (15.9 KT)

3.1.1 Thermal Measurements. No thermal measurements were accomplished. Calculated incident thermal energy (Section 2.3.4) at each exposure site is shown in Table 3.1.

3.1.2 Blink-Reflex Exposures. Chorioretinal burns were produced in 22 of 26 rabbits among the five exposure stations in this series (Table 3.2). Distances ranged between 2.9 and 8.1 miles. Lesion sizes ranged from about $\frac{1}{8}$ to 2 human optic disk diameters. Smaller (and apparently less-severe) lesions were encountered at increasing distances from the fireball, as theoretically predicted by the diminuation of image size and increasing atmospheric attenuation of thermal energy with distance. Four animals sustained double or dumbell-shaped burns (Figure 3.2), which were noted in earlier studies (Reference 1). This type of lesion is caused by movement of the eye during exposure to the flash. It has been estimated that the rabbit is susceptible to retinal burning at distances about 25 percent greater than those equally harmful to man (Reference 9). By analogy, the distance here of 8.1 statute miles extrapolates to 6.5 for man. Both burn size and the high incidence of burns (80 percent) at the farthest exposure site, David, indicates that burning could have been produced at somewhat greater distances under the conditions of this test.

Eight of ten rabbits at David (Table 3.3) sustained burns on viewing the first 289 to 437 msec of the detonation. For these intervals, dosage at the cornea is calculated at 81 to 99 mg cal/cm^2 (Section 2.3.4). Average values are 93 mg cal/cm^2 at 382 msec. Limited data at 300 msec (Table 3.4) indicates that the actual thermal yield was about 25 percent less than that predicted by the calculations herein. Accordingly, the range of corneal dosage is probably more nearly 61 to 74 mg cal/cm^2, or an average of about 67 mg cal/cm^2. Double burns sustained by Rabbits D-90 and D-54 indicate that lesions could have been produced by less-severe parameters of exposure than are presented here. This observa-

TABLE 3.1 A SUMMARY OF PARAMETERS OF BLINK-REFLEX EXPOSURES FOR ALL SHOTS TESTED BY PROJECT 4.1

Times to second maximum are measured values. Total incident thermal energy and percent of total incident thermal energy available during BRT were calculated (Section 2.3.4) except where otherwise indicated. Final values of incident thermal energy during BRT were brought into congruence with limited data at 300 msec (Table 3.4) through reducing the calculated values for Erie, Lacrosse, and Mohawk by 0.25, 0.33, and 0.6, respectively. The BRT measured at Erie was assumed for Lacrosse; that measured at Mohawk was assumed for multimegaton shots. The percent of incident thermal energy radiated during BRT was calculated according to Section 1.2.3 except as otherwise noted.

Shot:	Erie					Lacrosse	Mohawk		Zuni	Cherokee	Navajo	
Exposure Site:	Tom	Uriah	Van	Alvin	David	David	David	Yvonne	Nan	Nan	Nan	How
Yield, W, kt	15.9	15.9	15.9	15.9	15.9	43.9	340	340	3,500	3,900	4,400	4,400
Distance of Exposure Site, d, statute mi	2.7	3.0	3.8	4.9	8.1	8.9	14.4	7.5	12.9	21.6	16.1	10.6
Incident Thermal Energy at the Exposure Site, Q, mg cal/cm^2	1,800 *	1,400 *	820 *	450 *	130 *	72 †	570 ‡	3,400 ‡	1,600-2,000 §	1,000 §	?	< 1,000
Time of t_2-max, msec	112	112	112	112	112	163	460	460	1,900	1,450	2,160	2,160
Range of BRT, msec	289-437	289-437	289-437	289 437	289 437	289-437	250-454	250-454	250-454	250-454	250-454	250-454
Increment of Incident Thermal Energy Radiated during BRT, pct	62-76	62-76	62-76	62-76	62-76	46-62	15-28	15-28	0.5-1.5§	1.0-1.7§	1.0-1.5	1.0-2.0
Incident Thermal Energy Available During BRT, mg cal/cm^2	830-1,100	680-830	380-450	230-260	60-70	20-30	20-50	150-320	20-30	10-20	?	<10-20
Exposure Series Blink Reflex	+	+	+	+	+	0	0	+	0	0	0	0
Early Closing Shutters	¶	¶	¶	¶	+	0	¶	+	0	0	¶	0
Delayed Closing Shutters	¶	¶	¶	¶	+	0	¶	+	0	0	¶	0
Filter	0	+	+	0	0	0	0	+	0	0	0	0

* Transmission at 93 percent per statute mile.
† Transmission at 90 percent per statute mile. Calculated value reduced by two-thirds because ground shot.
‡ Refer to Section 3.2.1
§ NRDL
¶ No exposure
+ Burns
0 No burns

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tions of the experiment. The average BRT for the monkey at 160 msec is a little less than half of the average of 382 msec required for the rabbit to blink his eye. Human BRT has been variously reported from 50 to 100 msec and apparently overlaps the range for the monkey. These and other factors strongly suggest that the monkey should be used for chorioretinal burn studies in the future.

3.1.3 Early-Closing Shutters. Retinal burns were sustained by 8 of 27 rabbits exposed behind early-closing shutters at 8.1 miles on Site David (Table 3.5). Rabbits behind four malfunctioning shutters were considered as "no exposures." Burns were not encountered

TABLE 3.2 BLINK-REFLEX EXPOSURES. SIZES OF CHORIORETINAL BURNS SUSTAINED BY RABBITS AT VARIOUS DISTANCES FROM SHOT ERIE (15.9 KT)

Subjects viewed the fireball from its initiation for a period limited only by the blink reflex of the individual animal. The BRT at David ranged between 289 and 437 msec, averaging 382 msec among those animals sustaining burns (Table 3.3). All lesions are single except where shown as double. Size of lesions shown as fraction or multiple of human optic disk diameters (d.d.).

Position Number	Burn Production, Location of Site, and Distance in Statute Miles				
	Tom, 2.9 mi.	Uriah, 3.0 mi.	Van, 3.8 mi.	Alvin, 4.9 mi.	David, 8.1 mi.
1	2 d.d., severe	1 d.d., moderate	1 d.d., moderate, hemorrhage	1/3 d.d., moderate	no burn
2	double; 1 1/2 d.d., severe; 3/4 d.d., severe	double, 1/2 d.d., moderate; 1/2 d.d., moderate	1 1/2 d.d., moderate, hemorrhage	1 d.d., moderate	1/8 d.d., mild
3	no burn	1/2 d.d., moderate	animal escaped	2 1/2 d.d., moderate, hemorrhage	1/4 d.d., mild
4	dead on recovery	dead on recovery	2 d.d., moderate, hemorrhage	1/8 d.d., mild	no burn
5	dead on recovery	dead on recovery	1/2 d.d., moderate	1 d.d.	double; 1/8 d.d., mild; 1/3 d.d., moderate
6	no exposure	no exposure	no exposure	no burn	double, 1/8 d.d., mild; 1/8 d.d., mild
7	no exposure	no exposure	no exposure	no exposure	1/4 d.d., mild
8	no exposure	no exposure	no exposure	no exposure	1/4 d.d., mild
9	no exposure	no exposure	no exposure	no exposure	1/3 d.d., moderate
10	no exposure	no exposure	no exposure	no exposure	1/3 d.d., moderate

in any of the first fourteen exposures in the range of 0 to 7.5 through 0 to 59 msec. It was thought earlier that two animals might have sustained burns during the interval of the first pulse, 0 to 13.1 msec. One, however, proved to have resulted from shutter failure; the other was a case of uncertain retinal pigmentation, noted frequently in the gray rabbit.

Burns were first encountered in the increment of 0 to 67.5 msec, which corresponds to a calculated thermal dosage of the cornea of about 21 mg cal/cm^2. Four, or possibly five, of eight rabbits received burns in the range of 0 to 67.5 through 0 to 107 msec. The time of the maximum of the second pulse occurred at 112 msec. Beyond this period, four of the remaining five exposures resulted in burns. The extremely low incidence of burning (one of fifteen) until reaching the rapidly ascending portion of the second pulse discounts the contribution of the first flash to burn production under the conditions of the experiment.

3.1.4 Delayed-Opening Shutters. Three chorioretinal burns were sustained from ten exposures in this series of rabbits (Table 3.6). Four shutter failures and two cases of photographic film failure were considered as "no exposures." None of the exposures included the maximum of the first flash, which terminated at 13.1 msec. The time of the maximum thermal flux was at 112 msec. One minimal burn was produced by 112.5 msec of exposure to about 38 mg cal/cm^2 on the ascending portion of the second pulse. Another minimum lesion was sustained by 103 msec of exposure to about 20 mg cal/cm^2 on the descending segment of the pulse. A third (and somewhat larger) lesion, $\frac{1}{2}$ optic disk diameter, included both ascending and descending portion of the curve of the second pulse.

3.1.5 Filter Studies. Burns produced behind filters on Sites Uriah and Van at 3.0 and 3.8 miles, respectively, were somewhat similar in appearance to blink-reflex lesions sustained on Site David at 8.1 miles distance from ground zero (Tables 3.2 and 3.7). From this similarity it is inferred that the filters reduced the thermal rate and yield incident at the cornea at Uriah and Van to a level comparable to that at David.

All filters and combinations of filters tested either reduced the severity of, or prevented, burning. However, no conclusions are possible concerning the relative burn production of various segments of the thermal spectrum.

3.2 SHOT MOHAWK (340 KT)

3.2.1 Thermal Measurements. An incident thermal energy at 3,500 mg cal/cm^2 was measured at the Site Yvonne exposure station by equipment on loan from Project 8.3. The reliability of the measurement is not known, but is in agreement with 3,400 mg cal/cm^2 calculated at a transmission of 93 percent/mile for 7.5 statute miles. At David, a distance of 14.4 miles, an incident thermal energy of 900 mg cal/cm^2 was measured by the same equipment. At 93 percent transmission/mile, the calculated value is 572 mg cal/cm^2. The disparity between measured and calculated values may be attributed to instrumentation operating at its lower limit of resolution.

3.2.2 Blink-Reflex Exposures. Chorioretinal burns were produced in six of eight rabbits and eight of eight monkeys at Site Yvonne (Table 3.8), a distance of 7.5 statute miles from the fireball. This extrapolates for man to about 5.1 miles (based on the difference in focal distances of rabbit and man). Among the rabbits, lesion size was about the same as the diameter of the human optic disk. Minor hemorrhaging was observed in only one instance. These lesions appeared comparable in size and severity to those which were encountered at 3 to 5 miles distance from Shot Erie (Tables 3.1 and 3.2). Blink reflex time as determined from photography ranged from 250 to 454 msec, with an average of 362 msec. Corresponding thermal dosage at the cornea calculated at 510 to 990 mg cal/cm^2, or an average of 767 mg cal/cm^2.

The correlation of the size of burns with the fireball diameter is found in a comparison of the BRT data from Shot Mohawk with that from Shot Erie. Large burns of 1-human-disk diameter were produced by exposure to Shot Mohawk at Site Yvonne (7.5 miles from 340 kt of yield at a transmission of 90 percent/mile). At essentially the same distance, much smaller lesions averaging only $\frac{1}{4}$ human disk diameter were produced at Site David by Shot Erie (8.1 miles from 15.9 kt at essentially the same transmission). At this distance, the small difference of $\frac{1}{2}$ mile has a negligible effect upon the size of the fireball upon the retina, although the greater dosage sustained at Site Yvonne would account for some difference in size.

Burns were not produced in eight rabbits at Site David by Shot Mohawk, a distance of 14.4 miles. Accordingly, it is estimated that burns would not have been produced in man at 11.5 miles, except where less atmospheric attenuation prevails. Note is made that this condition obtains at high altitudes.

Although burns were not produced at Site David by Shot Mohawk, a distance of 14.4 statute miles, the incident thermal energy available during the blink reflex time is calculated at 80 to 160 mg cal/cm^2. This range appears sufficient to cause injury compared

TABLE 3.3 BLINK-REFLEX EXPOSURES. CHORIORETINAL BURN PARAMETERS FOR RABBITS AND MONKEYS AT 8.1 STATUTE MILES FROM SHOT ERIE (15.9 KT)

Exposure site was located on David Island. No hemorrhaging was observed. Size of burns are shown as fractions of human optic disk diameter (d. d.). Total thermal energy incident at the site (130 mg cal/cm^2) and thermal doses at the cornea were calculated according to Section 2.3.4.

Animal Number	Period of Exposure (Blink Reflex Time)	Calculated Thermal Dose at the Cornea	Size of Burn and General Description
	msec	mg cal/cm^2	
Rabbits:			
D-50	0 to 289	81	$\frac{1}{6}$ d. d., mild
D-52	0 to 375	92	$\frac{1}{4}$ d. d., mild
D-55	0 to 375	92	$\frac{1}{4}$ d. d., mild
D-90	0 to 380	93	double; $\frac{2}{3}$ d. d., moderate; $\frac{1}{6}$ d. d., mild
D-54	0 to 437	99	double; $\frac{1}{6}$ d. d., mild; $\frac{1}{6}$ d. d., mild
D-56	0 to 437	99	$\frac{1}{4}$ d. d., mild
D-51*			no burn
D-49*			no burn
A-21†			$\frac{1}{3}$ d. d., moderate
A-26†			$\frac{1}{3}$ d. d., moderate
Average:	382	93	
Monkeys:			
569	0 to 109	36	$\frac{1}{4}$ d. d., bilateral, mild
545	0 to 125	42	no burn
735	0 to 125	42	minimal, bilateral, mild
524	0 to 140	46	no burn
606	0 to 156	49	minimal, right eye, mild
745	0 to 156	49	minimal, right eye, mild
707	0 to 203	61	minimal, right eye, mild
712	0 to 312	83	$\frac{1}{4}$ d. d., bilateral, mild
Average:	160	51	

* Unable to determine BRT from photography.

† On water tower, 25 feet above main exposure site.

with 60 to 70 mg cal/cm^2, which caused ample burning at David during Shot Erie (Table 3.1). Reference to data at 300 msec (Table 3.4) shows that the measured energy is about a third of that calculated for the same time interval. Accordingly, the incident thermal energy for Mohawk at David adjusts to about 25 to 50 mg cal/cm^2, which might explain the lack of burns at 14.4 miles.

Among the monkeys, both eyes were burned in eight of eight animals. Double burns were encountered in two instances (Figure 3.2). In one case, minor hemorrhaging in one eye and, in another instance, central hemorrhaging in both eyes were observed. Lesions

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ranged in size between $1/8$ and 1 optic-disk diameter with the preponderance on the order of $1/2$ to 1 disk diameter.

3.2.3 Early-Closing Shutters. Retinal burns were sustained by 7 of 26 rabbits exposed behind the early-closing shutters at Site Yvonne (Table 3.9). Six exposure failures were counted as "no exposure."

The time for the minimum following the first pulse was 57 msec. It is noted that four of thirteen rabbits received burns during this period. In fact, two animals sustained retinal damage as early as the first 15.6 to 31.1 msec of the flash.

All of the lesions from the first pulse were mild and small, ranging from pin point to about $1/3$ human disk diameter in size. Although four animals sustained burns prior to 57 msec, no other burns were produced behind shutters that closed from 60 to 250 msec after time zero, except in one case at 109 msec limit, wherein a small double burn occurred. This apparent inconsistency in the data is unexplained. Two exposures at 0 to 952 msec resulted in equivalent lesions of 1 optic-disk diameter.

3.2.4 Delayed-Opening Shutters. Three, or possibly four, of sixteen rabbits sustained burns in this series (Table 3.10). The interval of 15.6 to 250 msec produced a doubtful lesion in one of two animals exposed. In two of two rabbits, the increment of 15.6 to 1,000 msec produced burns of essentially the same size and severity as those observed in the blink-reflex study. The interval of 485 to 635 msec caused a small mild burn in one of two animals. Although the animal was exposed only about half of its blink-reflex time, the dose rate was near the maximum for this shot. The time of the maximum was 460 msec. No burns were produced after the first 60 seconds of the flash.

TABLE 3.4 A COMPARISON OF CALCULATED VERSUS MEASURED THERMAL YIELD DURING FIRST 300 MSEC OF THE DETONATION*

Shot	Yield	Percent of Thermal at 300 msec	Thermal Yield Radiated in 300 msec if Total Thermal Yield is $1/3$ of Total Yield: TM 23-200	Measured
	kt		kt	kt
Erie	15.5	46	2.8	2.38
Lacrosse	40	33	6.2	4.40
Mohawk	350	6.5	11.6	7.57
Zuni, Cherokee	3,500	0.85	35	9.9
Navajo	4,700	0.80	31	12.5

* Data according to Weapon Effects Department, Sandia Corporation, Sandia Base, Albuquerque, New Mexico (ltr Symbol: 5110 (193) dated 7 Nov 56).

3.2.5 Filter Studies. Only two burns were produced in 27 exposures behind the fixed-density optical filters. These lesions were both $1/2$ human disk diameter in size and were of moderate severity. Neither burn was produced behind the least-protective filters (Table 3.11).

3.2.6 Protective Electronic Shutters, Electromechanical. Electromechanical, as well as the electrophysical shutters (to be discussed below), are developmental devices rather than prototypes or reproduction models. Evaluations on this project were intended to determine the effectiveness of their operation at their present stage of development. Information derived from Operation Redwing could serve as a guide for the development of future devices of this or similar nature.

Three shutters of this type were tested on each shot. The recorder, as described previously, was to provide a record of the actual shutter closing time and to give positive evidence that the shutters closed in the required time. This recording device did not

TABLE 3.5 EARLY-CLOSING SHUTTERS. CHORIORETINAL-BURN PARAMETERS FOR RABBITS EXPOSED AT 8.1 STATUTE MILES TO INCREASING INCREMENTS OF THE THERMAL PULSE FROM SHOT ERIE (15.9 KT)

Exposure site was located on David Island. No double lesions were produced. No hemorrhaging was observed. Size of burns shown as fractions of human optic disk diameter (d.d.). Total thermal energy at the exposure site (130 mg cal/cm²) and thermal doses at the cornea were calculated according to Section 2.3.4.

Animal Number	Period of Exposure: Desired	Period of Exposure: Actual	Calculated Thermal Dose at the Cornea	Size of Burn and Description
	msec	msec	mg cal/cm²	
D-1	0 to 7	0 to 7.5	3	no burn
D-2	0 to 7	0 to 7.5	3	no burn
D-25	0 to 7	0 to 7.5	3	no burn
D-26	0 to 7	0 to 7.5	3	no burn
Time of Minimum 13.1 msec				
D-3	0 to 10	0 to 18.8	5	no burn
D-4	0 to 10	shutter failure		1/4 d.d., mild
D-27	0 to 10	0 to 18.8	5	no burn
D-28	0 to 10	0 to 18.8	5	no burn
D-5	0 to 20	0 to 25.0	7	no burn
D-29	0 to 20	0 to 27.5	8	no burn
D-6	0 to 30	0 to 37.5	12	no burn
D-30	0 to 30	0 to 37.5	12	no burn
D-7	0 to 40	0 to 47.5	14	no burn
D-31	0 to 40	0 to 47.5	14	no burn
D-8	0 to 50	0 to 59.0	18	no burn
D-92	0 to 50	shutter failure		no burn
D-9	0 to 60	0 to 67.5	21	no burn
D-33	0 to 60	0 to 67.5	21	1/6 d.d., mild
D-10	0 to 70	0 to 77.5	26	no burn
D-34	0 to 70	0 to 80.0	27	1/3 d.d., mild
D-11	0 to 80	shutter failure		no burn
D-35	0 to 80	0 to 87.5	30	1/4 d.d., mild
D-12	0 to 90	0 to 96.3	33	edema (gray rabbit)
D-36	0 to 90	shutter failure		no burn
D-13	0 to 100	0 to 105	36	no burn
D-37	0 to 100	0 to 107	38	1/4 d.d., mild
Time of Second Maximum 112 msec				
D-14	0 to 120	0 to 127	43	1/4 d.d., mild
D-38	0 to 120	0 to 127	43	1/4 d.d., mild
D-15	0 to 250	0 to 258	73	1/8 d.d., mild
D-39	0 to 250	0 to 258	73	no burn
D-40	0 to 1,000	0 to 1,005	125	1/2 d.d., moderate

function properly on any test. There is no positive assurance that the shutters closed for Shots Cherokee, Zuni, Navajo, or Mohawk, although they were satisfactorily tested prior to each shot. None of the electromechanical shutters were operative for Shot Erie, due to an electrical short circuit and fire in the outlet panel. Project personnel were present at the exposure site during Shot Lacrosse and visually determined that the shutters did operate. In order to obtain some information on the order of closing time for these shutters under field conditions, advantage was taken of Shot Blackfoot to photograph an oscillograph tract of the shutter closure time. This was determined to be approximately 500 μsec and is in agreement with figures obtained in the laboratory.

Although the shutters were inoperative during Shot Erie, it is significant that no burns

TABLE 3.6 DELAYED-OPENING SHUTTERS. CHORIORETINAL-BURN PARAMETERS FOR RABBITS EXPOSED AT 8.1 STATUTE MILES TO VARIOUS SEGMENTS OF THE THERMAL PULSE FOLLOWING THE FIRST MAXIMUM FROM SHOT ERIE (15.9 KT).

Exposure site was located on David Island. No double lesions were produced. No hemorrhaging was observed. Size of burns shown as fractions or multiples of human optic disk diameter (d. d.). Total thermal energy at the exposure site (130 mg cal/cm^2) and thermal doses at the cornea were calculated according to Section 2.3.4).

Animal Number	Period of Exposure Desired	Period of Exposure Actual	Duration of Exposure	Calculated Thermal Dose at the Cornea	Size of Burn and Description
	msec	msec	msec	mg cal/cm^2	
Time of Minimum, 13.1 msec					
D-17	10 to 100	12.5 to 125	112.5	38	minimal, mild
D-41	10 to 100	12.5 to 103	90.5	31	no burn
D-18	10 to 250	shutter failure			1/4 d. d., mild
Time of Second Maximum, 112 msec					
D-84	10 to 250	*			1/4 d. d., moderate
D-80	10 to 1,000	*			1/2 d. d., moderate
D-82	10 to 1,000	12.5 to 1,010	997.5	125	1/2 d. d., moderate
D-20	200 to 300	205 to 319	114.0	23	no burn
D-44	200 to 300	222 to 325	103.0	20	minimal
D-21	500 to 600	505 to 588	83.0	5	no burn
D-45	500 to 600	505 to 588	83.0	5	no burn
D-24	1,000 to 1,100	shutter failure			no burn
D-46	1,000 to 1,100	1,040 to 1,145	105.0	< 5	no burn
D-23	2,000 to 2,100	2,005 to 2,140	135.0	< 5	no burn
D-47	2,000 to 2,100	shutter failure			no burn
D-22	5,000 to 5,100	1,005 to 1,195	90.0	< 5	no burn
D-48	5,000 to 5,100	shutter failure			no burn

* Shutter timing photography obscured by flash.

TABLE 3.7 FILTER EXPOSURES. CHORIORETINAL-BURN PRODUCTION IN RABBITS AT VARIOUS DISTANCES FROM SHOT ERIE (15.9 KT)

Subjects viewed the fireball from its initiation for a period limited only by the blink reflex time. The blink reflex time was not determined for this series. No double lesions were produced. No hemorrhaging was observed. Size of burns shown as fraction or multiples of human optic disk diameter (d. d.).

Filter	Burn Production, Location of Site, and Distance in Statute Miles				
	Tom, 2.7 mi.	Uriah, 3.0 mi.	Van, 3.8 mi.	Alvin, 4.9 mi.	David, 8.1 mi.
4 G*	no burn	no burn	no exposure	no exposure	no burn
4 G*	no burn	1/3 d. d., moderate	no exposure	no exposure	no burn
2 N†	no burn	1/2 d. d., moderate	1/8 d. d., mild	no burn	no burn
2 N†	no burn	no burn	no exposure	no burn	no burn
R + IR ‡	no burn	1/4 d. d., moderate	1/3 d. d., moderate	no exposure	no burn
R + IR ‡	no burn	no exposure	no burn	no exposure	no burn
IR §	no burn	no exposure	1/3 d. d., moderate	no exposure	no burn
IR §	no exposure	no exposure	no burn	no exposure	no burn

* Green ‡ Combination red transmitting and infrared absorbing
† Neutral § Infrared absorbing

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were received. From this fact, in conjunction with supporting theoretical calculations, it may be inferred that the 60-to-65 percent attenuation of the shutter in the open position was sufficient to reduce the thermal dose incident on the cornea to a level below the retinal-burn threshold.

Under the experimental conditions that prevailed, it may be inferred that the electromechanical shutter can offer satisfactory protection against retinal burns. It is not

TABLE 3.8 BLINK-REFLEX EXPOSURES. CHORIORETINAL-BURN PARAMETERS FOR RABBITS AND MONKEYS AT 7.5 STATUTE MILES FROM SHOT MOHAWK (340 KT)

Exposure site was located on Site Yvonne. Size of burns are shown as fractions of human optic disk diameter (d. d.). Total thermal energy incident at the site (3,400 mg cal/cm^2) and the thermal doses at the cornea were calculated according to Section 2.3.4.

Animal Number	Period of Exposure	Calculated Thermal Dose at the Cornea	Size of Burn and Description
	msec	mg cal/cm^2	
Rabbits:			
E-50	0 to 250	510	1 d. d., moderate to severe
D-46	0 to 266	510	no burn
E-54	0 to 360	780	no burn
E-53	0 to 391	850	1 d. d., severe, hemorrhage
E-56	0 to 391	850	1 d. d., severe
E-49	0 to 422	880	1 d. d., moderate to severe
E-55	0 to 454	990	1 d. d., moderate to severe
E-51*			1 d. d., moderate to severe
Average:	0 to 362	767	
Monkeys:			
691	0 to 109	200	bilateral; 1 d. d., moderate to severe; 1 d. d., moderate to severe
809	0 to 109	200	bilateral; 1/8 d. d., mild; 1/8 d. d., mild
545	0 to 109	200	bilateral; 1/2 d. d., moderate; 1/2 d. d., moderate
701	0 to 156	340	bilateral; double; 1/2 d. d., moderate; 1/2 d. d. moderate; 1/2 d. d. moderate; 1/2 d. d. moderate
713	0 to 250	510	bilateral; double; 1/4 d. d., moderate; 1 d. d. moderate; 1/2 d. d., moderate; 1+ d. d., moderate
571	0 to 422	840	bilateral; 1+ d. d., moderate; 1+ d. d., moderate; hemorrhage
740	0 to 516	1,200	bilateral; 3/4 d. d., mild to moderate; 3/4 d. d. mild to moderate
794	0 to 672	1,300	bilateral, 1 d. d., severe, hemorrhage; 1 d. d., severe, hemorrhage
Average:	0 to 293	684	

* Unable to determine blink-reflex exposure from photography

possible to make a positive conclusion until these devices have been further tested and evaluated.

Detailed information on this shutter will be reported by the contractor at the completion of the present developmental contract.

3.2.7 Protective Electronic Shutters, Electrophysical. Four shutters of this type were tested on three shots in the megaton range (Cherokee, Zuni, and Navajo) at Sites

TABLE 3.9 EARLY-CLOSING SHUTTERS. CHORIORETINAL-BURN PARAMETERS FOR RABBITS EXPOSED AT 7.5 STATUTE MILES TO INCREASING INCREMENTS OF THE THERMAL PULSE FROM SHOT MOHAWK (340 KT)

Exposure site was located on Site Yvonne. One double lesion was produced. No hemorrhaging was observed. Size of burns are shown as fractions of human optic disk diameter (d. d.). Total thermal energy at the exposure site (3,400 mg cal/cm²) and thermal doses at the cornea were calculated according to Section 2.3.4.

Animal Number	Period of Exposure		Calculated Thermal Dose at the Cornea	Size of Burn and Description
	Desired	Actual		
	msec	msec	mg cal/cm²	
E-25	0 to 5	0 to 15.6	<34	no burn
A-97	0 to 5	0 to 15.6	<34	no burn
E-1	0 to 5	0 to 15.6	<34	no burn
E-2	0 to 5	0 to 15.6	<34	minimal, mild
E-27	0 to 10	0 to 15.6	<34	no burn
A-4	0 to 10	0 to 31.1	34	minimal, mild
E-3	0 to 10	0 to 15.6	<34	no burn
E-4	0 to 10	did not close	3,400	1 d. d., moderate
E-29	0 to 20	0 to 31.1	34	no burn
E-5	0 to 20	0 to 31.1	34	no burn
E-30	0 to 30	0 to 31.1	34	1/3 d. d., mild
D-46	0 to 30	0 to 31.1	34	no burn
E-31	0 to 40	0 to 46.9	100	1/8 d. d., mild
E-7	0 to 40	0 to 46.9	100	no burn
Time of minimum 57 msec				
A-78	0 to 50	0 to 62.5	140	no burn
E-8	0 to 50	closed at time zero	none	no burn
E-23	0 to 60	0 to 62.5	140	no burn
E-9	0 to 60	0 to 62.5	140	no burn
D-10	0 to 70	closed at time zero	none	no burn
E-10	0 to 70	0 to 78.1	140	animal out of position
E-35	0 to 80	closed at time zero	none	no burn
E-11	0 to 80	0 to 78.1	140	no burn
A-49	0 to 90	0 to 93.6	170	no burn
E-12	0 to 90	0 to 93.6	170	?
A-52	0 to 100	0 to 109	200	double; 1/8 d. d., mild; 1/8 d. d., mild
E-13	0 to 100	0 to 109	200	no burn
E-38	0 to 120	closed at time zero	none	no burn
D-3	0 to 120	0 to 125	240	no burn
D-18	0 to 250	0 to 15,850	>3,000	no burn
D-41	0 to 250	0 to 250	510	no burn
Time of second maximum 460 msec				
E-40	0 to 1,000	0 to 952	1,800	1 d. d., moderate
D-47	0 to 1,000	0 to 952	1,800	1 d. d., moderate

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TABLE 3.10 DELAYED-OPENING SHUTTERS. CHORIORETINAL-BURN PARAMETERS FOR RABBITS EXPOSED AT 7.5 STATUTE MILES TO VARIOUS SEGMENTS OF THE THERMAL PULSE FOLLOWING THE FIRST MAXIMUM FROM SHOT MOHAWK (340 KT)

Exposure site was located on Site Yvonne. No double lesions were produced. No hemorrhaging was observed. Size of burns are shown as fractions or multiples of human optic disk diameter (d.d.). Total thermal energy at the exposure site (3,400 mg cal/cm^2) and thermal doses at the cornea were calculated according to Section 2.3.4.

Animal Number	Period of Exposure		Duration of Exposure	Calculated Thermal Dose at the Cornea	Size of Burn and Description
	Desired	Actual			
	msec	msec	msec	mg cal/cm^2	
Time of Minimum 57 msec					
A-17	10 to 100	15.6 to 93.6	78.0	140	no burn
D-45	10 to 100	15.6 to 109	93.4	170	no burn
E-42	10 to 250	15.6 to 250	234.4	480	no burn
E-18	10 to 250	15.6 to 250	234.4	480	minimal (?)
E-43	10 to 1,000	15.6 to 952	936.4	1,700	1 d.d., moderate
D-1	10 to 1,000	15.6 to 1,000	984.4	1,800	½ d.d., moderate
E-44	200 to 300	203 to 297	94.0	240	no burn
A-7	200 to 300	203 to 282	79.0	200	no burn
Time of Second Maximum 460 msec					
E-45	500 to 600	485 to 563	78.0	200	out of position
E-21	500 to 600	485 to 625	140.0	270	¼ d.d., mild
E-46	1,000 to 1,100	952 to 1,079	127.0	200	no burn
A-1	1,000 to 1,100	952 to 1,079	127.0	200	no burn
E-47	2,000 to 2,100	1,910 to 1,985	75.0	34	no burn
E-86	2,000 to 2,100	1,890 to 2,030	140.0	100	no burn
E-48	5,000 to 5,100	4,740 to 4,830	90.0	140	no burn
E-25	5,000 to 5,100	4,720 to 4,820	100.0	140	no burn

TABLE 3.11 FILTER EXPOSURES. CHORIORETINAL-BURN PRODUCTION IN RABBITS AT A SINGLE DISTANCE FROM SHOT MOHAWK (340 KT)

Subjects viewed the fireball from its initiation for a period limited only by the blink reflex time. The blink reflex time was not determined for this series. No double lesions were produced. No hemorrhaging was observed. Size of burns shows as fractions or multiples of human disk diameter (d.d.).

Filter	Site Yvonne, 7.5 mi., Burn Production and Distance in Statute Miles	Filter	Site Yvonne, 7.5 mi., Burn Production and Distance in Statute Miles
4 G	no burn	3.8 N	no burn
4 G	no burn	3.8 N	no burn
4 G	no burn	4.6 N	no burn
5 G	no burn	4.6 N	no burn
5 G	no burn	4.6 N	no burn
5 G	no burn		
6 G	no burn	5.8 B	no burn
6 G	½ d.d., moderate	5.8 B	no burn
6 G	no burn	5.8 B	no burn
2 N	no burn	2 N + IR	no burn
2 N	no burn	2 N + IR	no burn
2 N	no burn	2 N + IR	no burn
2.4 N	no burn		
2.4 N	no burn		
2.4 N	½ d.d., moderate		
3.8 N	no burn		

Nan and How. Results on all three tests were inconclusive, as no burns were obtained with or without protection.

Several deficiencies that should guide future development have been noted: (1) The aperture is too small. (2) The field of view is extremely constricted. (3) The light attenuation of the device in the open position appears to be sufficiently high to prevent burns at the distances tested, even though the shutter remains open. (4) No means are provided to indicate whether the shutter functions at shot time.

All four shutters were tested completely and worked satisfactorily prior to each shot.

Detailed information on this shutter will be reported by the contractor at the completion of the present developmental contract (Reference 11).

3.3 SHOTS CHEROKEE, ZUNI, AND NAVAJO

No burns were produced by the multimegaton shots, despite the relatively high incident thermal energy received at the exposure station in at least two instances. According to Table 3.1, 1,000 and 1,600 mg cal/cm^2, respectively, were produced by Cherokee and Zuni at Site Nan, where no burns were encountered. Shot Erie (15.9 kt) by contrast, caused ample retinal burning at Site David, with an incident thermal energy of only 130 mg cal/cm^2. Further examination of the data shows that the burns by Shot Erie at Site David were produced by 60 to 70 mg cal/cm^2, delivered during the first 289 to 437 msec of the detonation, i.e., the period of the blink reflex. Cherokee and Zuni, by contrast, produced only 10 to 30 mg cal/cm^2 during essentially the same interval. Although this level was apparently not sufficient to cause burning, it was sufficient to cause blinking, which protected against the remainder of the second pulse. The lack of burn production by the multimegaton shots precludes an estimate of the threshold parameters for chorioretinal burning by bursts of this range of yield.

Chapter 4

CONCLUSIONS and RECOMMENDATIONS

4.1 CONCLUSIONS

Chorioretinal burns were produced at distances greatly exceeding the limits for any other prompt and significant biologic effects of nuclear detonations. The problem of chorioretinal burns is one of increasing significance at higher altitudes, where lack of atmospheric attenuation increases not only radiant exposure, but also both the rate at which radiant energy is delivered and the distance to which a given amount can be transmitted.

The distance at which burning is produced in the EPG was less than that anticipated from the results of Operation Upshot-Knothole at the NTS, where burns were encountered at distances as great as 42.5 miles from ground zero. The lesser range at the EPG may be due to higher atmospheric attenuation from excessive humidity.

The blink-reflex time for rabbits, monkeys, and man is not sufficient to protect against the flash from small and intermediate-range (350-kt) devices. The energy of the first pulse of intermediate-yield weapons can produce burns.

The air burst from a 20-kt device at dawn of a clear day (90 percent transmission/mile) is sufficient to produce chorioretinal burns at 8.1 miles for rabbits and monkeys and, by extrapolation, at 6.5 miles for man. Under comparable conditions, a nuclear device of 350-kt yield can cause chorioretinal burning at 7.6 miles in animals, equivalent to 5.1 miles for man. It is probable, in the case of both devices, that burns can be produced in man at greater distances, but not as far as 11.5 miles, except where atmospheric transmission is greater than 90 percent/mile. Additional information is needed in order to establish the limiting parameters for burns over the entire range of yield.

Fixed-density optical filters reduce the caloric dose and dose rate incident on the eye and, therefore, the incidence of chorioretinal burns. No conclusion can be reached regarding the relative effectiveness of filters having various spectral transmission.

Although the results from protective shutters were inconclusive with respect to protection against chorioretinal burns, information was obtained invaluable for the future development of these devices.

4.2 RECOMMENDATIONS

The loss of life incurred among animals placed in exposure boxes open to direct sunlight 12 to 14 hours before H-hour, as well as the inability to control blinking by animals due to reflected light striking the unexposed eye, indicates the advisability of using a light-tight, airconditioned trailer as an exposure facility in this type of study. A trailer is specified in order to permit rapid change of station according to distance requirements. At least two, and preferably three, exposure sites echeloned in depth should be employed for each shot, and provision should be made for the measurement of incident thermal energy at the exposure station.

Pigmented rabbits used in studies of ocular effects must be carefully examined ophthalmoscopically for normal, as well as pathological, variation prior to use. Certain color types, particularly gray, have irregular pigmentation of the ocular fundus, which causes difficulty in detecting minimal lesions.

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